

Compendium of Current Single Event Effects Results for Candidate Spacecraft Electronics for NASA

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Abstract— Sensitivity of a variety of candidate spacecraft electronics to proton and heavy ion induced single event effects is presented. Devices tested include digital, linear, and hybrid devices.

Index Terms—Single Event Effects, spacecraft electronics, digital, linear bipolar, and hybrid devices.

I. INTRODUCTION

In order to meet the demands of reduced cost, higher performance and more rapid delivery schedules imposed by the space flight community, commercial and emerging technology devices have assumed a prominent role in meeting these needs. The importance of ground-based testing of such devices for susceptibility to single event effects (SEE) has assumed greater importance. The novel ways in which some of these devices are used also highlights the need for application specific testing to ensure their proper operation and ability to meet mission goals.

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The studies discussed here were undertaken to establish the sensitivities of candidate spacecraft electronics to heavy ion and proton-induced single event upset (SEU), single event latchup (SEL), and single event transients (SET). For proton displacement damage (DD) and total ionizing dose (TID) results, see a companion paper submitted to the 2007 IEEE NSREC Radiation Effects Data Workshop entitled: "Compendium of Current Total Ionizing Dose Results and Displacement Damage Results for Candidate Spacecraft Electronics for NASA" by D. Cochran, et al. [1].

II. TEST TECHNIQUES AND SETUP

A. Test Facilities

All SEE tests were performed between February 2006 and February 2007. Heavy ion experiments were conducted at Lawrence Berkeley National Laboratory (LBNL) [2], at Texas A&M University Cyclotron (TAMU) [3], and at the Single Event Effects Test Facility (SEETF) at the National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University (MSU) [4]. The LBNL and TAMU facilities use an 88" cyclotron. The NSCL MSU facility uses tandem K500 and K1200 cyclotrons to deliver on target ions with energies up to 125 MeV/u. All these facilities are suitable for providing a variety of ions over a range of energies for testing. The DUT was irradiated with heavy ions having linear energy transfers (LETs) ranging from 0.59 to 120 MeV•cm²/mg. Fluxes ranged from 1x10³ to 1x10⁷ particles/cm²/s, depending on the device sensitivity. Representative ions used are listed in Table I. LETs between the values listed were obtained by changing the angle of incidence of the ion beam with respect to the DUT, thus changing the path length of the ion through the DUT and the "effective LET" of the ion [5]. Energies and LETs available varied slightly from one test date to another.

Proton SEE tests were performed at two facilities: the University of California at Davis (UCD) Crocker Nuclear Laboratory (CNL) [6], and at the Indiana University Cyclotron Facility (IUCF) [7]. Proton test energies incident on the DUT are listed in Table II. Proton SEE tests were performed in a manner similar to heavy ion exposures. However, because protons cause SEE via indirect ionization of recoil particles, results are parameterized in terms of proton energy rather than LET. Because such proton-induced nuclear interactions are rare, proton tests also feature higher cumulative fluence and particle flux rates than do heavy ion experiments.

TABLE I: HEAVY ION TEST FACILITIES AND TEST HEAVY IONS

	Ion	Energy (MeV)	Surface LET in Si, MeV•cm ² /mg (Normal Incidence)	Range in Si (μm)
LBNL	O ¹⁸	184	2.2	227
	Ne ²²	216	3.5	175
	Ar ⁴⁰	400	9.7	130
	Cu ⁶⁵	659	21	110
	Kr ⁸⁶	886	31	110
	Xe ¹³⁶	1330	59	97
	10 MeV per AMU tune			
MSU	Xe ¹²⁴	17360	14.1	~ 3300
TAMU	Ne ²⁰	300	2.5	316
	Ar ⁴⁰	599	7.7	229
	Cu ⁶³	944	17.8	172
	Kr ⁸⁴	1259	25.4	170
	Xe ²⁹	1934	47.3	156
	15 MeV per AMU tune			
	Ne ²⁰	800	1.2	1655
	Ar ⁴⁰	1598	3.8	1079
	40 MeV per AMU tune			

TABLE II: PROTON TEST FACILITIES

University of California at Davis (UCD) Crocker Nuclear Laboratory (CNL), energy ranged from 5 to 63 MeV, flux ranged from 8x10 ⁷ to 1x10 ⁹ particles/cm ² /s.
Indiana University Cyclotron Facility (IUCF), energy ranged from 50 to 200 MeV, flux ranged from 1x10 ⁷ to 8x10 ⁸ particles/cm ² /s.

B. Test Method

Unless otherwise noted, all tests were performed at room temperature and with nominal power supply voltages. We recognize that high-temperature and worst-case power supply conditions are recommended for single event latchup (SEL) device qualification.

1) SEE Testing - Heavy Ion:

Depending on the DUT and the test objectives, one or more of three SEE test methods were typically used:

Dynamic – the DUT was exercised continually while being exposed to the beam. The events and/or bit errors were counted, generally by comparing DUT output to an unirradiated reference device or other expected output (Golden chip or virtual Golden chip methods). In some cases, the effects of clock speed or device operating modes were investigated. Results of such tests should be applied with caution due to the application-specific nature of the results.

Static – the DUT was loaded prior to irradiation; data were retrieved and errors were counted after irradiation.

Biased – the DUT was biased and clocked while I_{CC} (power consumption) was monitored for SEL or other destructive effects. In most SEL tests, functionality was also monitored.

In SEE experiments, DUTs were monitored for soft errors, such as SEUs and for hard errors, such as SEL. Detailed descriptions of the types of errors observed are noted in the individual test results [8].

SET testing was performed using a high-speed oscilloscope. Individual criteria for SETs are specific to the device being tested. Please see the individual test reports for details [8].

Heavy ion SEE sensitivity experiments include measurement of the Linear Energy Transfer threshold (LET_{th}) and saturation cross section at maximum measured LET. The LET_{th} is defined as the maximum LET value at which no effect was observed at an effective fluence of 1x10⁷ particles/cm². In the case where events are observed at lower fluences for the smallest LET tested, LET_{th} will either be reported as less than the lowest measured LET or determined approximately as the LET_{th} parameter from a Weibull fit.

2) SEE Testing - Proton

Proton SEE tests were performed in a manner similar to heavy ion exposures. However, because protons cause SEE via indirect ionization of recoil particles, results are parameterized in terms of proton energy rather than LET. Because such proton-induced nuclear interactions are rare, proton tests also feature higher cumulative fluences and particle flux rates than do heavy ion experiments.

III. TEST RESULTS OVERVIEW

Abbreviations and conventions are listed in Table III. Abbreviations for principal investigators (PIs) are listed in Table IV, and SEE results are summarized in Table V. Unless otherwise noted, all LETs are in MeV•cm²/mg and all cross sections are in cm²/device. This paper is a summary of results. Complete test reports are available online at <http://radhome.gsfc.nasa.gov> [8].

TABLE III: ABBREVIATIONS AND CONVENTIONS:

H = heavy ion test
 P = proton test (SEE)
 Samp = sample
 P.I. = principal investigator
 LDC = lot date code
 DUT = device under test
 LET = linear energy transfer ($\text{MeV}\cdot\text{cm}^2/\text{mg}$)
 LET_{th} = linear energy transfer threshold (the minimum LET value for which a given effect is observed for a fluence of 1×10^7 particles/ cm^2 – in $\text{MeV}\cdot\text{cm}^2/\text{mg}$)
 $< =$ SEE observed at lowest tested LET
 $> =$ no SEE observed at highest tested LET
 σ = cross section ($\text{cm}^2/\text{device}$, unless specified as cm^2/bit)
 $\sigma_{\text{max measured}}$ = cross section at maximum measured LET ($\text{cm}^2/\text{device}$, unless specified as cm^2/bit)
 App. Spec. = application specific
 Aux = auxiliary
 CMOS = complementary metal oxide semiconductor
 DDR = double data rate
 FPGA = field programmable gate array
 I/O = input/output
 LVDO = low voltage drop out
 MMIC = monolithic microwave integrated circuit
 MOSFET = metal oxide semiconductor field effect transistor
 N/A = not applicable
 NAND = not and (electronic logic gate)
 Op Amp = operational amplifier
 PAL = programmable array logic
 pHEMT = p-type high electron mobility transistor
 PPC = power PC
 SDRAM = synchronous dynamic random access memory
 SEBE = single event burst error
 SEE = single event effect
 SEFI = single event functional interrupt
 SEGR = single event gate rupture
 SEL = single event latchup
 SET = single event transient
 SEU = single event upset
 V_{IN} or V_{OUT} = input voltage or output voltage

TABLE IV: LIST OF PRINCIPAL INVESTIGATORS

Principal Investigator (PI)	Abbreviation
Steve Buchner	SB
Melanie Berg	MB
Jim Howard	JH
Ray Ladbury	RL
Timothy Oldham	TO
Christian Poivey	CP
Anthony Sanders	AS

TABLE V: SUMMARY OF SEE TEST RESULTS

Part Number	Manufacturer	LDC	Technology/ Device Function	Process	Particle: (Facility/Date) P.I.,	Test Results LET in MeV·cm ² /mg σ in cm ² /device, unless otherwise specified	App. Spec. Test (Y/N)	Supply Voltage	Samp. Size	Test Report
Programmable Logic/FPGA										
Eclipse FPGA	Aeroflex	1059 and 1082	0.25 μ m CMOS shift register	CMOS	H: (TAMU06MAY) MB; H: (TAMU06NOV) MB; H: (LBNL07JAN) MB; P: (IU06MAR) MB	H: 8.5<SEU LET _{th} <12; P: SEU LET _{th} <5x10 ⁻¹⁶ with 195 MeV Protons. No errors observed at lower energies.	N	Core 2.5V; I/O 3.3V	10	T022205_Aeroflex_Eclipse_V2
RTAX-S	Actel	0506 and 0543	0.15 μ m CMOS FPGA	CMOS	H: (TAMU06MAY) MB; P: (IU06MAR) MB	H: SEU LET _{th} <8.5 (will be higher if running at a slower frequency); P: SEU σ ~8.5x10 ⁻¹⁶ with 195 MeV; 6.6x10 ⁻¹⁶ with 63 MeV Protons at 150 MHz; No SEUs observed at 15 MHz at both 63 and 195 MeV Protons.	N	Core: 1.5 V, I/O: 3.3 V	10	T110405_RTAX
LX25	Xilinx	0553	Virtex IV FPGA 90nm CMOS flip chip	CMOS	H: (TAMU06MAY) MB; H: (TAMU06JUN) MB; H: (TAMU06AUG) MB; P: (IU06MAR) MB; P: (IU06JUL) MB	H: SEL LET _{th} >75; SEFI LET _{th} <5.7; P: No SEL observed at both 93 and 195 MeV Protons.	N	Core 1.2V; I/O 3.3V	1	I032706_LX25
XC4VFX60	Xilinx	0629(MSU), 0609(TAMU)	Virtex IV FPGA 90 μ m CMOS	CMOS	H: (MSU06OCT) CP; H: (TAMU07FEB) CP	SEL LET _{th} >58; SEFI LET _{th} <5.7; SEFI σ_{max} measured =1x10 ⁻² with embedded PPC.	Y	Core 12V; I/O 3.3V; Aux 2.5V	2(MSU), 3(TAMU)	M102506_XC4VFX60 , T021607_XC4VFX60
AT22V10	ATMEL	0437A	PAL	1nm BiCMOS	H: (TAMU06AUG) CP	1 failure at LET 106; 2 failures at LET 53; SEU LET _{th} <2.8; SEU σ >1x10 ⁻³	N	5V	4	T082606_ATF22V10
Linear Devices										
RH137H	Linear Technology	0235	Negative Adjustable Regulator	Bipolar	H: (TAMU06MAY) CP	SET LET _{th} >76 with the 33 μ F output capacitor; SET LET _{th} ~20 without output capacitor; Positive and negative transients observed; SET σ >3x10 ⁻³	Y	Vin -15V; Vout -12V	2	T052306_RH137
TPS76701	Texas Instruments	LDC unknown – no package markings	Voltage Regulator	BiCMOS	H: (LBNL06JUN) CP	SEL LET _{th} >83; SET LET _{th} <3.45; SET σ ~2x10 ⁻³	N	Vin 3.3V; Vout 1.5V	3	L061606_TPS76701 ; [13]
TPS73601	Texas Instruments	LDC not indicated	Low dropout linear adjustable voltage regulator	BiCMOS	H: (LBNL06JUN) CP	SEL LET _{th} >59; SET LET _{th} <2 at highest load current (I _{out} =250mA), SET sensitivity increased with load current; SET σ ~1x10 ⁻³ (worst case)	N	Vin 3.3V; Vout 1.5V	2	L061806_TPS73601 ; [13]
SAT8605R	SatCon Electronics	LDC unknown – no package markings	2.5 linear voltage regulator	Hybrid	H: (LBNL06JUN) CP	SEL LET _{th} >59; SET LET _{th} <21; SET σ ~8x10 ⁻⁴	N	Vin 3.3V; Vout 1.5V	2	L061606_SAT8605R ; [13]
RH1013	Linear Technology	0343A	Op Amp	Bipolar	H: (TAMU06NOV) CP	SEU LET _{th} ~76; SET LET _{th} ~10; SET σ ~3x10 ⁻⁴	Y	+/-15V	2	T111606_RH1013
MAX997	Maxim	0531	Voltage Comparator	Bipolar	H: (TAMU06NOV) AS	SEL LET _{th} >76; SEU LET _{th} <2.8	Y	4.3V and 5V	2	T111906_MAX997ESA
RHFL4913	ST Microelectronics	0510A	Bipolar LVDO Regulator	Bipolar	H: (TAMU06NOV) AS	SEL LET _{th} >76 (full loading); SEU LET _{th} <12.3 (no load) and >4 (300mA and 600mA loading); SET σ_{max} measured ~2.9x10 ⁻⁵ (no load); ~1.26x10 ⁻⁴ (300mA loading); and ~5.3x10 ⁻⁵ 600mA loading)	Y	3.3V and 5V	2	T111806_RHFL4913
ACT8601	Aeroflex	No LDC (hybrid)	Dual voltage regulator RH117 and RH137	Bipolar	H: (LBNL06JUN) SB	SEL LET _{th} >59; SET LET _{th} >59	Y	+/-12V inputs; +/-9V outputs	1	L061806_ACT8601
TL431	Texas Instruments	No LDC; die pkg at GSFC	Programmable Shunt Regulator	Bipolar	H: (LBNL06JUN) SB	SEL LET _{th} >59; SET LET _{th} <3.3; SET σ_{max} measured ~3x10 ⁻³ at LET 59	Y	3.67V	2	L061806_TL431
LMH6702	National Semiconductor	No LDC Info on package	High Speed Op Amp	Bipolar	H: (LBNL06JUN) SB	SEL LET _{th} >81; SET LET _{th} ~10; SET σ_{max} measured ~7x10 ⁻⁶ at LET 81	Y	3.8V	1	L061806_LMH6702
RH1499	Linear Technology	0220	Op Amp	Bipolar	H: (LBNL06JUN) SB	SEL LET _{th} >58.7; SET LET _{th} <3; SET σ_{max} measured ~4x10 ⁻³ at LET 58.7	N	+/-15V	2	L061806_RH1499
AD549	Analog Devices	0535	Ultralow Input-Bias Current Operational Amplifier	Bipolar	H: (LBNL06SEP) AS	SEL LET _{th} >83.7; SET LET _{th} <58.7	Y	15V	3	L091906_AD549

TABLE V: SUMMARY OF SEE TEST RESULTS (CONT.)

Part Number	Manufacturer	LDC	Technology/ Device Function	Process	Particle: (Facility) P.I.,	Test Results LET in MeV·cm ² /mg σ in cm ² /device, unless otherwise specified	App. Spec. Test (Y/N)	Supply Voltage	Samp. Size	Test Report
Optocouplers										
HCPL625K	Agilent Technologies	0534	Optocoupler; 4 channels logic gate	AlGaAs LED	P: (IU06MAR) CP	SET $\sigma = 1 \times 10^{-7}$ cm ² /channel; Proton energy threshold <100	Y	5V	4	I032706_HCPL625K
HCPL-6751	Agilent Technologies	0251	Power MOSFET Optocouplers	Hybrid	P: (UCD06OCT) JH	P: No SETs observed up to a fluence of 1×10^{12} with 63 MeV protons	N	5V	3	D102506_HCPL6751
Memories										
NAND01GW3B2ANGE	ST Microelectronics	0604	1 Gb Micro Flash	CMOS	H: (LBNL07JAN) TO; P: (IU06JUL) TO/RL	H: SEL LET _{th} < 55; SEU LET _{th} > 3; SEU $\sigma_{\text{max measured}} = 1.1 \times 10^{-11}$ cm ² /bit at LET 58.7 (static) P: No SEL observed with 200 MeV Protons; SEU $\sigma \sim 1$ to 3×10^{-10} up to a fluence of 1×10^{11} with 200 MeV Protons;	N*	3.3V	1	I072706_NAND01GW3B2ANGE L012707_NAND01GW3B2ANGE
K9F4G08U0A	Samsung	0625	4 Gb Flash	CMOS	H: (LBNL07JAN) TO	SEL LET _{th} > 55; SEU LET _{th} ~ 3.4; SEU $\sigma_{\text{max measured}} = 5 \times 10^{-11}$ cm ² /bit (static); SEU $\sigma_{\text{max measured}} = 7.5 \times 10^{-11}$ cm ² /bit (dynamic)	N*	SEL: 3.3V SEU: 3.0V	3	L012607_K9F4G08U0A [9]
KH41G0X38	Samsung	0546	1 Gbit DDR SDRAM	90 nm minimum feature size CMOS	H: (TAMU06JUN) RL; P: (IU06JUL) RL	H: SEL 45 < LET _{th} < 108; P: $\sigma \sim 4 \times 10^{-19}$ cm ² /bit at 200 MeV	N*	2.5V	2	T062806_I072806_KH41G0X38
Communication Devices										
TLK2711	Texas Instruments	0545	Transceiver	CMOS	H: (LBNL06SEP) JH	SEL LET _{th} > 58.8; SEU LET _{th} = 1.5 transmit and 1.1 receive; $\sigma_{\text{max measured}} = 5.4 \times 10^{-5}$ transmit and 3.75×10^{-5} receive; SEBE LET _{th} = 2.2; $\sigma_{\text{max measured}} = 5.4 \times 10^{-5}$ for both transmit and receive; Loss of sync LET _{th} = 1.5; $\sigma_{\text{max measured}} = 1.5 \times 10^{-5}$ for both transmit and receive;	Y	2.5V	2	L092106_TLK2711
Power Devices										
SHD85202	Sensitron	0321	Dual power MOSFET driver	Bipolar/CMOS/DMOS	H: (LBNL06JUN) JH	SEL LET _{th} > 58.8; SET LET _{th} < 20 at room temp. and <10 at 100 degrees Celsius.	Y	12V	3	L061706_SHD85202
53111	Micropac	0103	Power MOSFET Optocouplers	Hybrid	H: (TAMU06NOV) JH; P: (UCD06OCT) JH	H: SEL LET _{th} < 83.4; SEGR LET _{th} < 83.4 MOSFET; No SET testing of opto due to device construction P: No SETs observed up to a fluence of 1×10^{12} with 63 MeV protons	Y	0V, 28V, and 34V	P: 3; H: 2;	D102506_T111606_53111
MSAFX11P50A	Microsemi	0644	Power MOSFET	MOSFET	H: (TAMU07FEB) CP	No SEGR at 0V and -425V at LET 20.6	N	N/A	10	T021907_MSAFX11P50A
Special Devices										
OMH3075B	Optek Technology	SN0011, SN0137, and SN0136	Hallogic Hall Effect Sensor	Bipolar	H: (LBNL06SEP) AS	SEL LET _{th} > 83; SET LET _{th} < 58.7; SET $\sigma_{\text{max measured}} \sim 4.6 \times 10^{-4}$ (5V), and 2.1×10^{-4} (24V) at LET 83	Y	5V and 24V	3	L091906_OMH3075B
TGL4302	Triquint	No LDC; die pkg at GSFC	MMIC voltage variable attenuator	pHEMT MMIC	H: (TAMU06AUG) SB	SEL LET _{th} > 78.4; SET LET _{th} > 78.4	Y	10V	1	T082806_TGL4302
Discrete Devices										
2N2222	Microsemi	0315	Transistor	Bipolar	H: (LBNL06JUN) SB	SEL LET _{th} > 58.72; SET LET _{th} ~ 20; SET $\sigma_{\text{max measured}} \sim 2.1 \times 10^{-4}$ at LET 58.72	N	8V	1	L061806_2N2222

N* = Test data taken in limited operating modes. It is recommended that application specific tests be performed.

IV. TEST RESULTS AND DISCUSSION

As in our past workshop compendia of GSFC test results, each DUT has a detailed test report available online at <http://radhome.gsfc.nasa.gov> [8] describing in further detail, test method, SEE conditions/parameters, test results, and graphs of data.

This section contains a summary of testing performed on a selection of featured parts.

1) Agilent Technologies HCPL625K Four Channels Logic Gate Optocoupler

The HCPL625K four-channel logic gate optocoupler was tested for proton-induced SET susceptibility at IUCF. The HCPL625K optocoupler has a 5MHz bandwidth. Previous data [10] shows that fast optocouplers (>10 MHz bandwidth) are sensitive to proton-induced SET, but that slow optocouplers (about 400 KHz bandwidth) are not sensitive to proton-induced SET. In the latter case, optocoupler bandwidth is too low to propagate SETs to device output. No data were available for optocouplers with bandwidth in between these two ranges. Test data show that HCPL is sensitive to proton-induced SETs. SET cross-section curves are shown in Fig. 1. Generally, we see one type of transient where the phototransistor is in the off state and is turned on. This is the case shown in Fig. 2 where the optocoupler is on and its output is high. In this bias condition, measured cross-section is 1×10^{-7} cm²/channel. A typical SET when the device is on is shown in Fig. 2. The HCPL 625K is also susceptible to SET when the phototransistor is on and the device is in the off state (low output). In that case the SET probably occurs in the device logic gate output. The SET sensitivity is significantly lower in this configuration. The Maximum measured cross-section is about 2×10^{-9} cm²/channel. A typical SET when device is off is shown in Fig. 3. [11]

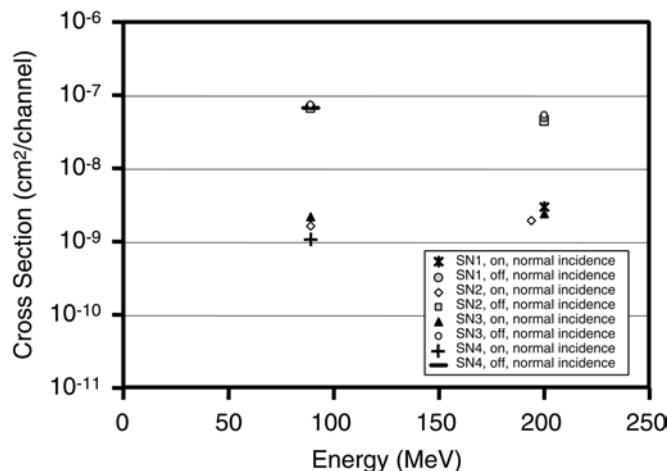


Fig. 1. HCPL625K SET cross-section curves. Cross-section is given for one channel.

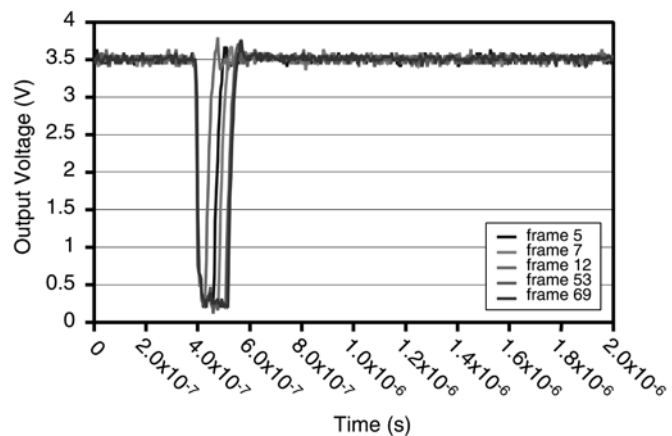


Fig. 2. HCPL625K Typical SET waveforms when optocoupler is on.

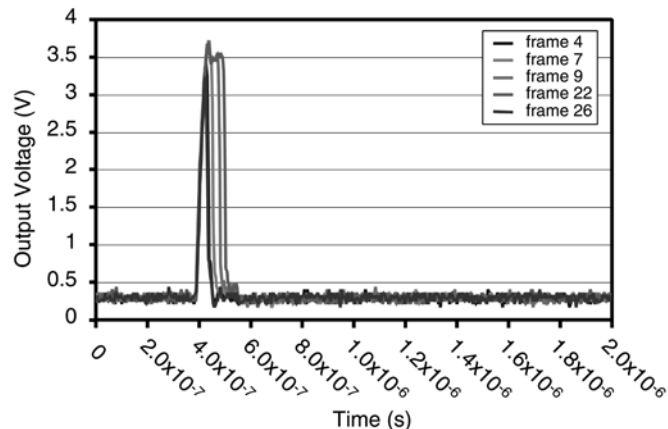


Fig. 3. HCPL625K Typical SET waveform when optocoupler is off.

2) Recent LVDO Voltage Regulators SEE Results

As with other bipolar analog devices, voltage regulators are known to be sensitive to single event transients (SET). In typical applications large output capacitors are used to provide noise immunity. Therefore, SET amplitude and duration are generally small, and are often of secondary importance. However, even small SETs are a concern for low voltage applications. Over-voltages may cause destructive conditions. Under-voltage may cause functional interrupt and may also trigger electrical latchup conditions. In addition, internal protection circuits which are affected by load as well as internal thermal effects can also be triggered from heavy ions, causing dropouts or shutdown ranging from milliseconds to seconds [12].

Tested devices are presented in table VI. Satcon device is an hybrid developed for the space market. TI devices are commercial parts. All parts have internal protection circuitries for thermal and over current effects.

TABLE VI: LVDO DEVICES TESTED

Type	Manufacturer	Output Voltage (V)	Output Current (A)
SAT8605R	SatCon Electronics	1.5V	3
TPS76701	Texas Instruments	adjustable	1
TPS73601	Texas Instruments	adjustable	0.4

The parts were tested at LBL with a 10 MeV/u beam. Devices under test (DUT) were biased with an input voltage of 3.3V and an output voltage of 1.5V under different load conditions. Output capacitor values were those recommended in manufacturer data sheets. More detailed results are available in [13].

Fig. 4 shows SAT8605R SET cross sections with a 1000 μ F output capacitor. We can't see a significant effect of output current on SAT8605R sensitivity. However, SAT8605R is not sensitive for an output current lower than 100 mA.

Only one transient waveform was observed. Fig. 5 shows typical transients. The Maximum SET amplitude is 450 mV. The worst case transient duration is 6 μ s.

Fig. 6 shows TPS76701 SET cross sections for a 10 μ F output capacitor. We can't see a significant effect of output current on device SET sensitivity. However, for high output current values, heavy ions trigger device internal protection circuitries.

Fig. 7 shows the worst case SET. The device output goes down from 1.5V to 0V. In some cases protection circuitries are triggered and the device output is off for several milliseconds. About 20% of SETs are long duration transients.

Fig. 8 shows the SET cross sections for a 10 μ F output capacitor. SET sensitivity is higher for high output current values. SET sensitivity is negligible for 10 mA output current. As for TPS76701, for high output currents (> 100 mA), heavy ions trigger device internal protection circuitries.

Fig. 9 shows the worst-case transients. The device is shutdown for up to 100 ms. All SETs are long duration transients.

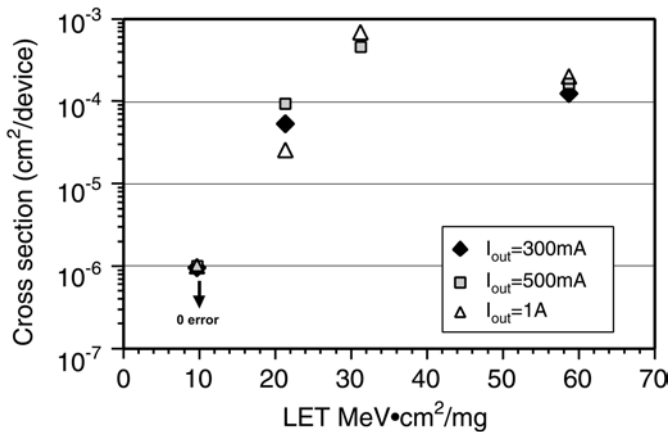


Fig. 4. SAT8605R SET cross-section.

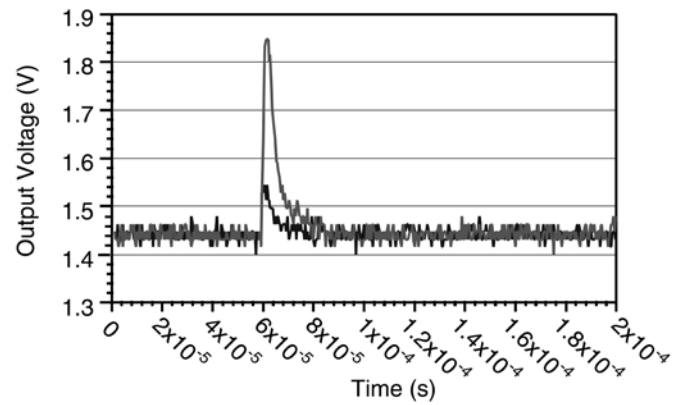


Fig. 5. SAT8605R typical SET.

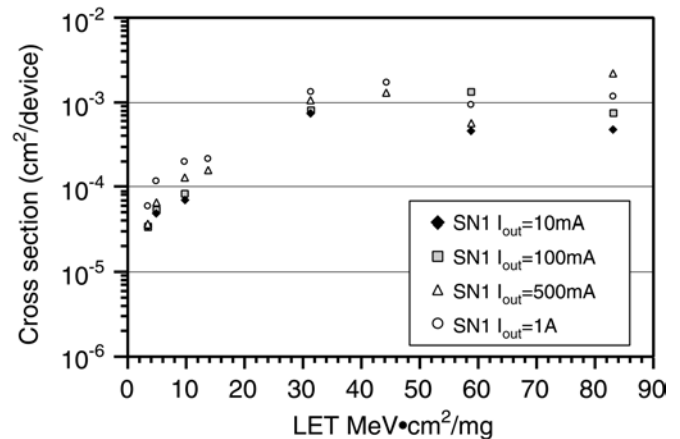


Fig. 6. TPS76701 SET cross-section.

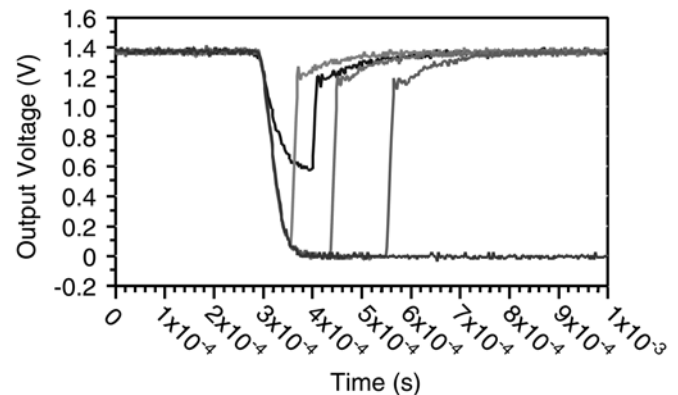


Fig. 7. TPS76701 SET waveforms, I_{out}=1A, at LET=83 MeV·cm²/mg.

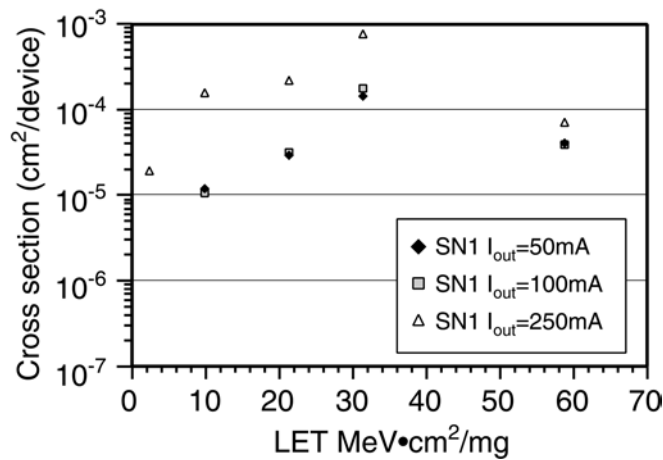
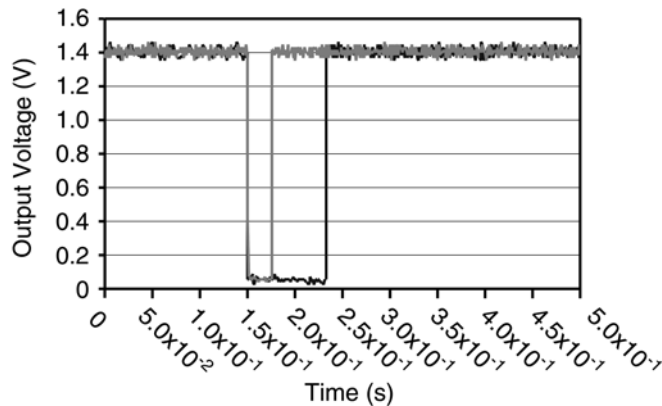


Fig. 8. TPS73601 SET cross-section curves.

Fig. 9. TPS73601 worst case SETs, $I_{out}=250mA$, at $LET=2.2 \text{ MeV}\cdot\text{cm}^2/\text{mg}$.

3) Samsung K9F4G08U0A 4 Gb Flash Memory

The results in Fig. 10 were fitted with Weibull parameters, threshold $LET = 3.5 \text{ MeV}\cdot\text{cm}^2/\text{mg}$, saturation cross section $= 5 \times 10^{-11} \text{ cm}^2/\text{bit}$, width = 27, exponent = 5, and CREME96 was used to calculate the bit error rate for geosynchronous orbit at solar minimum. The result was 1×10^{-12} errors/bit-day, which is equivalent to about 1.5 bit errors per year for a four Gb memory. The data in Fig. 10, is normalized per device (instead of per bit) so that the SEFI and destructive effects can be shown on the same scale as the bit upset cross section. Obviously, the SEFI and destructive error cross sections are much less than the bit upset cross section, and the error rate expected in space will scale with the cross section.

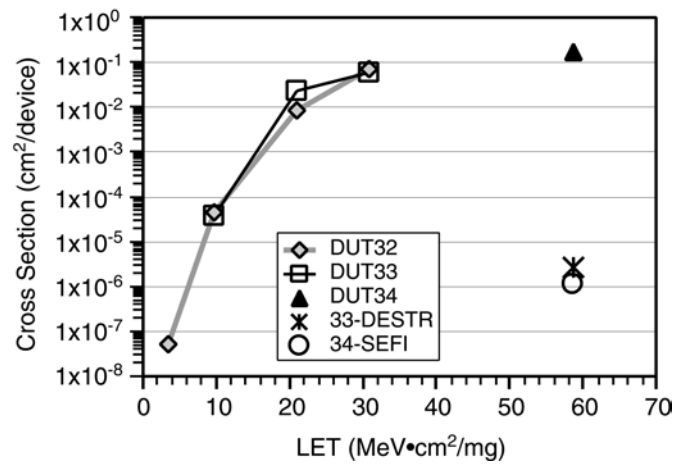


Fig. 10. Samsung K9F4G08U0A static upset cross sections.

4) Microsemi MSAFX11P50A P channel MOSFET

Radiation performance of the 500V, 11A, P channel MOSFET MSAFX11P50A from Microsemi was measured at TAMU. 10 parts were irradiated. 5 out of 10 were irradiated using 1858 MeV Krypton ($LET = 20.6 \text{ MeV}\cdot\text{cm}^2/\text{mg}$ and Range = 284 μm). Fig. 11 shows the last passing value and the first failing value on the 5 parts tested with this ion at this energy. Safe operating area is based on this condition. [14]

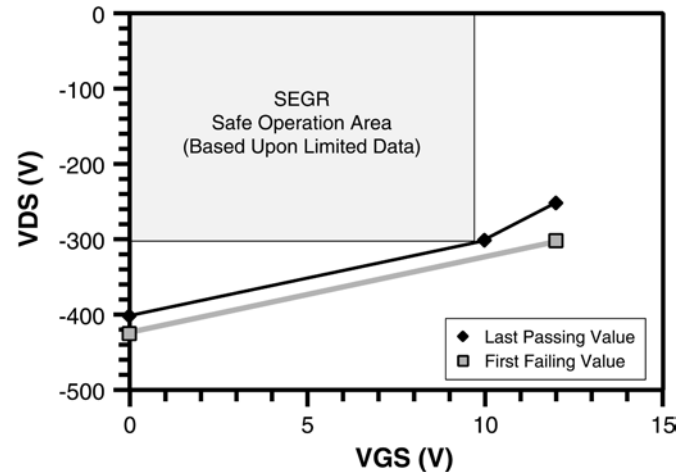


Fig. 11. MSAFX11P50A Krypton test results showing last passing and first failing value. Safe operating area is based upon this condition.

One device was irradiated with 860 MeV Krypton ($LET=30 \text{ MeV}\cdot\text{cm}^2/\text{mg}$ and Range = 108 μm). Three parts were irradiated with 2758 MeV Xenon ($LET = 40.7 \text{ MeV}\cdot\text{cm}^2/\text{mg}$ and Range=237 μm). Two devices were irradiated with 929 MeV Argon ($LET = 5.7 \text{ MeV}\cdot\text{cm}^2/\text{mg}$ and Range = 445 μm).

Data show that the dominant failure mode is Single Event Gate Rupture (SEGR) and that device operation at $VGS < 10V$ and $VDS < -300V$ provides a relatively safe operating region when irradiated with Krypton and Argon. Krypton represents an upper boundary of concern for space applications. There was a significant decrease in the device operational voltages between Kr and Xe with a safe operating region at $VGS = -5V$ and $VDS < -100V$. [14]

TABLE VII: MICROSEMI MSAFX11P50A SEE TEST SUMMARY

Ion Spec.	Ion Energy (MeV)	Serial Number	Last Passing Value (VGS,VDS)	First Failing Value (VGS,VDS)	SEE Failure Threshold (VGS,VDS)	Failing Nodes
Kr	1858	1	(0V, -425V)	(0V, -450V)	(0V, -437V)	*
Kr	1858	2	(10V, -300V)	(12V, -300V)	(11V, -300V)	(G, D)
Kr	1858	3	(0V, -475V)	(0V, -500V)	(0V, -488V)	(G, D)
Kr	1858	4	(12V, -250V)	NA	NA	NA
Kr	1858	4	(0V, -420V)	(0V, -440V)	(0V, -430V)	(G)
Kr	1858	5	(12V, -250V)	NA	NA	NA
Kr	1858	5	(0V, -420V)	NA	NA	NA
Kr	860	5	(0V, -420V)	NA	NA	NA
Kr	860	5	(12V, -250V)	NA	NA	NA
Kr	860	5	(0V, -480V)	NA	NA	NA
Kr	1858	5	(0V, -460V)	(0V, -480V)	(0V, -470V)	(G)
Xe	2758	6	(0V, -100V)	(0V, -125V)	(0V, -112V)	
Xe	2758	7	(5V, -100V)	(6V, -100V)	(5.5V, -100V)	
Xe	2758	8	(46V, 0V)	(48V, 0V)	(47V, 0V)	(G)
Ar	929	9	(0V, -480V)	(0V, -500V)	(0V, -490V)	(D)
Ar	929	10	(0V, -480V)	(0V, -500V)	(0V, -490V)	

V. SUMMARY

We have presented recent data from SEE on a variety of mainly commercial devices. It is the authors' recommendation that this data be used with caution. We also highly recommend that lot testing be performed on any suspect or commercial device.

VI. ACKNOWLEDGMENT

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